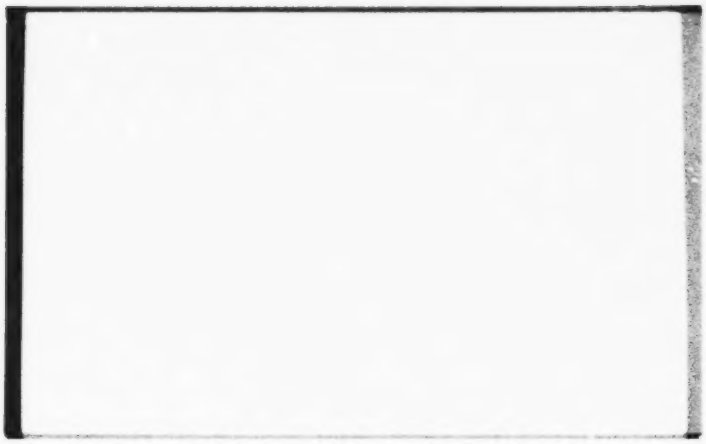
ENERGY USE ENGINEERING DEPARTMENT

PROJECT 7918

OIL PRODUCTION FROM NATURAL GAS AND COAL

ENERGY CONSERVATION DIVISION

B.C. HYDRO AND POWER AUTHORITY



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ENERGY USE ENGINEERING DEPARTMENT
ENERGY CONSERVATION DIVISION
B.C. HYDRO AND POWER AUTHORITY

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PROJECT 7918

OIL PRODUCTION FROM NATURAL GAS AND COAL

SYNOPSIS:

Methanol and gasoline can be produced commercially from natural gas. Such treatment downgrades a refined fuel and is not good energy conservation practice.

Liquids can be produced from coal at a price in line with that of imported oil. The liquid yield using proven synthesis methods is about 2 bbls/ton of coal. The yield from hydropyrolysis is about 3 - 3.5 bbls/ton. Hydropyrolysis techniques are not expected to be developed commercially until the 1990's, however.

A choice of coal liquefaction method could thus be influenced by the amount of time available for advantage to be taken of the more efficient hydropyrolysis technology.

PROJECT:

Initiated/Requested by:	T. J. Newton
Date Completed:	1981 January 8
Completed by:	C. F. Mason
Supervised by:	M. W. Bodnar
Approved by:	R. W. Racine, Manager Energy Use Engineering
Initial Distribution:	T. J. Newton R. W. Racine E. Haydock, H.O. Library

139/11

Canadian Cataloguing in Publication Data

Main entry under title:
Oil production from natural gas and coal

Caption title.
"Date completed: 1981 January 8".
Bibliography: p.
"Project 7918"
ISBN 0-7719-9175-4

1. Coal liquefaction. 2. Liquefied natural gas. I. B.C. Hydro. Energy Use Engineering Dept.

TP352.044 662'.662 C83-092105-2

D76-439

ENERGY USE ENGINEERING DEPARTMENT

PROJECT SUMMARY

PROJECT NO. 7918 PRIORITY 4

TITLE: Oil Production from Natural Gas and Coal

INITIATED/REQUESTED BY: R. W. Racine

ASSIGNED TO: C. F. Mason ASSIGNED BY: M. W. Bodnar

DATE ASSIGNED: 16 October 1979 DATE REQUIRED: Interim - May 1980
Final - Nov. 1980

ESTIMATED COMPLETION: COMPLETED: 1981 January 8

OBJECTIVES AND NOTES:

In the interim report review the technology and a summary of the present state of the process. The final report should include a technological review, environment considerations, economic evaluation, marketing prospects, recommendations and summary.

COPIES TO: DEPARTMENT MANAGER (THEN RECORD FILE), BLUE FILE, SUPERVISOR, (M. W. Bodnar),
T. J. Newton R. Schneider

EUE Supervisors

C. F. Mason

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1. SUMMARY

The technology is now available to convert natural gas and coal to liquids, at a cost reportedly in line with the price of imported oil.

Mobil Oil has commercialized a process in which methanol, produced from natural gas, may be converted to gasoline. Conversion of natural gas to liquids is a degradation of a refined fuel involving an energy loss and as such is contrary to energy conservation practice.

The most efficient technologies (hydroliquefaction) for conversion of coal to liquid fuels are at the pilot stage and are not expected to be available commercially much before 1990. Synthesis methods are proven but inherently inefficient.

If Canada is to use coal liquefaction as a means of becoming independent of imported liquid fuels the present choice is between either an inefficient but proven technology or more efficient method(s) for which time and development work are required to eliminate major problem areas.

The thermal efficiencies realized in practice of various conversion processes are shown in the following table. (Thermal efficiency is the percentage of energy in the prime fuel (natural gas or coal) that is recovered in the product).

Prime Fuel	Product	Type of Process	Efficiency
Natural Gas	Methanol	Various	60-65%
Natural Gas	Gasoline	Mobile MTG	56-58%
Coal	Liquids	Hydroliquefaction	61-71%
Coal	Liquids	Pyrolysis	51-61%
Coal	Liquids	Synthesis	35-45%

2. RECOMMENDATIONS

2.1 The conversion of natural gas to liquid fuels is a wasteful use of a refined energy source. (Energy losses are incurred in both the process and subsequent use of the liquid fuel.) Such conversions should be discouraged.

In most cases, natural gas can be put to better use as a direct replacement for oil as a heating fuel.

2.2 The world research effort in coal liquefaction is vigorous and progress is rapid. Close monitoring of research developments is therefore essential.

2.3 The three most promising American coal liquefaction processes - H-Coal, SRC-II, Exxon Donor Solvent - could be commercially available by 1990. Their suitability for use with Canadian coals should be examined.

2.4 Perhaps the greatest promise for synthesis processes, at least from the technical point of view, lies in Mobil's methanol-to-gasoline process. The economics need further study. Developments in this process should be followed closely.

The production of methanol from coal would free some natural gas for other uses.

2.5 If Canada is to opt for liquefaction in the future it will first be necessary to improve our understanding of Canadian coals.

2.6 The possibility of installing coal liquefaction plants with capacities less than estimated optimum of 100,000 bbl/day should be considered if the local or regional benefits could justify the government subsidies required or if coal liquefaction economics improved substantially.

2.7 Economic information relating to Canadian conditions for coal liquefaction is lacking and there is a need for detailed studies on the many aspects of synthetic fuels based on coal.

3. INTRODUCTION

Canada relies almost exclusively on crude oil from natural sources for its liquid fuel supply, the only other current source being synthetic oil from oil sands. Not until the mid-1980's will more than 10% of total domestic oil demands be met by oil sands plants.

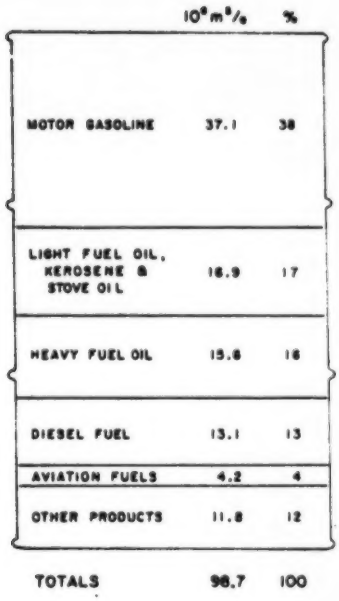

Figure 1 - Sales of refined petroleum products in Canada in 1978 ($1 \times 10^6 m^3/a$ equals about six million barrels a year) (Reference 1)

A major goal of the national energy policy is to eliminate oil imports, which currently account for about 34% of domestic requirements. Additionally, there is a need, in the long term, to have proven technology available to produce synthetic liquid fuels when oil supplies from natural resources are exhausted.

Natural gas, oil sands, heavy oils, coal and biomass are possible alternate sources of synthetic liquid fuels and can produce a wide variety of fuels and chemicals, depending on the nature and extent of processing.

Canada's liquid fuel sales are summarized in Figure 1.

Figure 2 indicates where refining capacity is located and what percentage of the crude petroleum is met by imports.

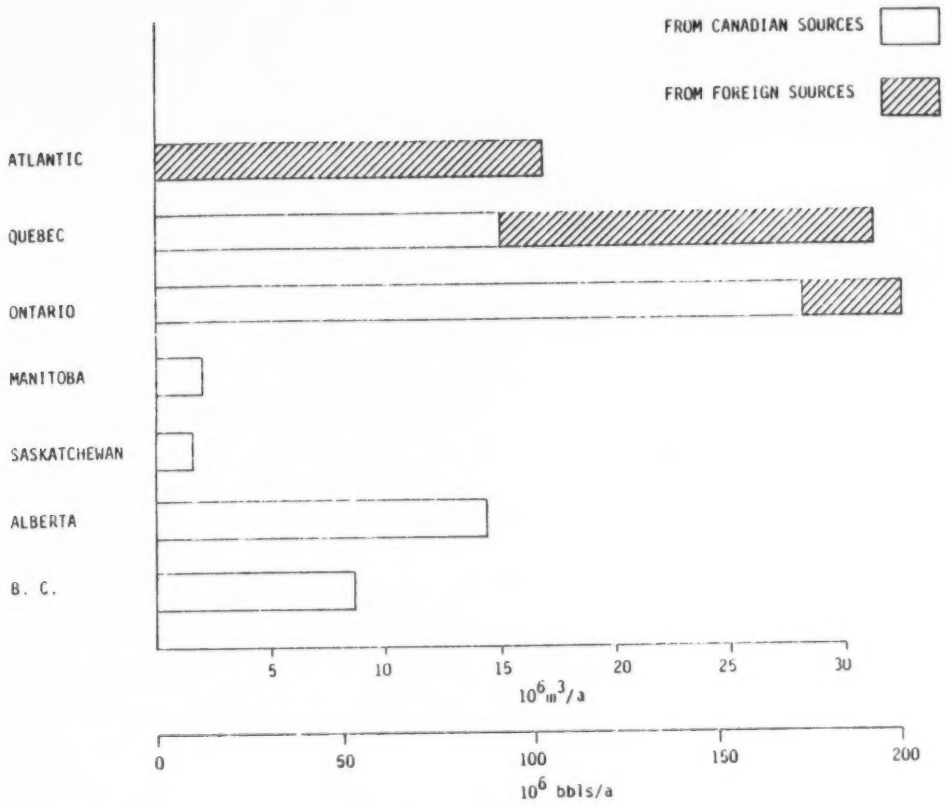

Figure 2 - Refinery capacity and source of feedstock, by province or region, 1978. (Reference 1)

National Energy Board projections of demands for liquid fuels up to 1995 are shown in Figure 3. It will be noted that diesel fuel accounts for most of the projected increase.

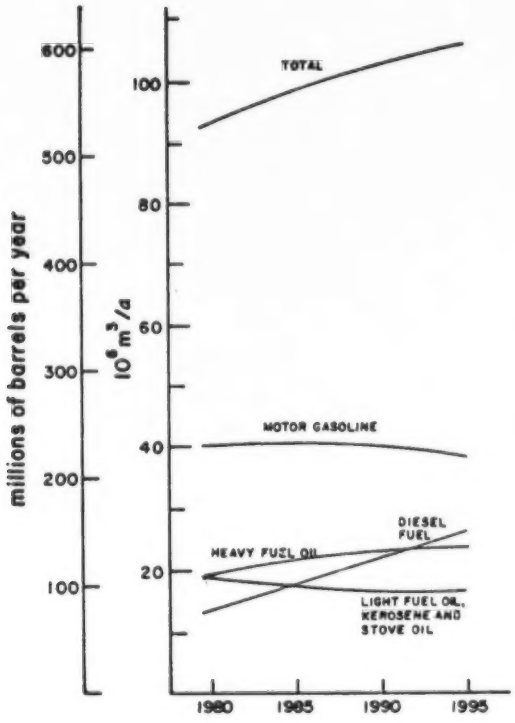

Figure 3 - Projected liquid fuel demands to 1995
(National Energy Board, 1978)

Conversion of any fossil fuel feedstock to liquid fuels entails some loss of energy because of process inefficiency. With coal, for example, the loss is 30 - 65%, depending on the process used. Because one objective of the national energy strategy is to conserve energy by making better use of the resource, priority in energy projects must be based to some degree on the efficiency with which each option can contribute to liquid fuel supply. Additionally, each option would have to be evaluated with respect to other factors such as economics, environment, social impact and technological soundness before any particular conversion process could be deemed the most preferable.

Currently, the New Zealand government has announced plans for a major gasoline-from-natural gas production facility to come on stream in 1984-85. The only commercial coal liquefaction operation in the world is in South Africa, where a plant has been in operation for over 25 years. The projects in New Zealand and South Africa are justified only because of local circumstances. Elsewhere, natural gas liquefaction on a commercial scale is confined to methanol production and coal liquefaction is only on the pilot scale because the alternatives are more attractive.

4. LIQUEFACTION - BASIC PRINCIPLES

The two components of fossil fuels which are of primary interest to energy conversion are hydrogen and carbon. As Figure 4 indicates, lighter products such as natural gas and gasoline have higher hydrogen-to-carbon (H/C) ratios than do heavy liquids and solids.

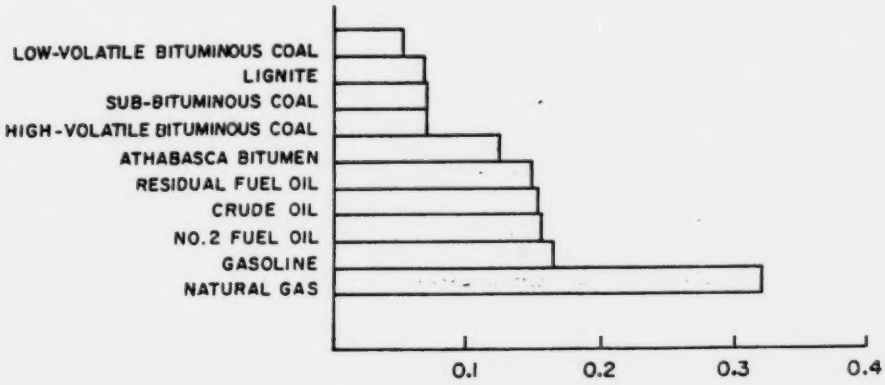

Figure 4 - Typical hydrogen-to-carbon ratios by weight for Canadian fossil fuels and refined products

To convert natural gas to liquids, it is evident from Figure 4 that the chemistry of the process should result in a reduction in the H/C ratio. Conversely, the conversion of coal to liquids requires an increase in the H/C ratio - either by removal of carbon or by addition of hydrogen.

5. LIQUIDS FROM NATURAL GAS

5.1 Methanol

Methanol (methyl alcohol, CH_3OH) is used in the manufacture of glues and resins. There is currently much interest in methanol as an automotive fuel, either directly as an additive to or replacement for gasoline, or for conversion into gasoline (Ref. Section 5.2).

With minor engine modifications, conventional automobiles could use up to 15% methanol in gasoline. Methanol's limitation is its property of separating out from a methane/gasoline blend in the presence of water. Under these conditions, the methanol and water fall to the bottom of an automobile's gas tank and the engine will stall. Use of 100% methanol in engines would entail substantial engineering changes.

For methanol production, natural gas is first allowed to react with steam in a reformer furnace to produce a synthesis gas - preferably two parts hydrogen to one of carbon monoxide. These are then combined to form methanol. It may also be formed when carbon dioxide is combined with hydrogen.

Using methane as the basic raw material, the following reactions occur:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

$$CO + 2H_2O \rightarrow CH_3OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Figure 5 is a diagram of the Commercial Solvents process for methanol production. Various other processes are in commercial operation.

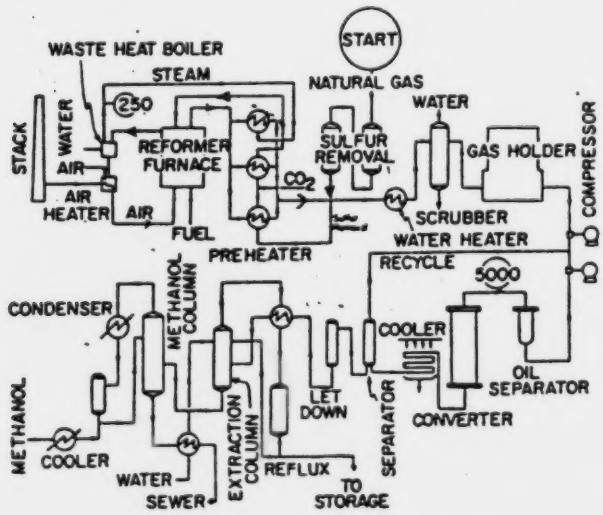

Figure 5 - Process for Methanol Production

In Canada about 3 or 4% of natural gas production is used to make methanol.

5.2 Gasoline

The Mobil Oil Co. has recently developed a one-step catalytic process (MTG) to produce gasoline from methanol.

The chemistry of the methanol conversion consists essentially of the systematic removal of water from methanol in the presence of a catalyst to produce, ultimately, a blend of paraffins, cycloparaffins and aromatics. The product, M-gasoline, is a high quality transportation fuel which meets the requirements for unleaded premium.

The key to the MTG process is the selectivity of the zeolite catalyst which permits only the required chemical reactions to proceed.

Mobil has been operating a 4 bbl/day pilot plant in New Jersey since 1976 and a 45,000 bbl/day plant has been underway since 1979.

The New Zealand natural gas-methanol-gasoline project (referred to in Section 3.0) will use the MTG technology with a fixed-bed catalytic reactor. Ultimate production will be up to 12,500 bbls/day - about one third of that country's gasoline requirements. The overall efficiency of the process (natural gas-methanol-gasoline) should be about 56 - 58% (assuming 60 - 64% efficiency for the methanol production step).

Mobil have an alternative system at the pilot plant stage which uses a fluidized-bed, rather than a fixed-bed. Compared with the fixed bed system, the fluid-bed system is reportedly more efficient, lower in capital cost, can give a higher gasoline yield and the product may be more accurately selected. Scaling up of the fluidized-bed system for commercial requirements has yet to be proven, however (Reference 2).

The main disadvantage of the Mobil process is its inability to produce diesel and jet fuel directly.

M-gasoline's cost in New Zealand is about $26/bbl compared with $38 -40/bbl for Fischer-Tropsch products (Ref. Section 6.2.1). Natural gas price in New Zealand is about $1.12/GJ.

6. COAL LIQUEFACTION

The increase in H/C ratio required for the liquefaction of coal can be brought about by either a degradation or a synthetic route (Figure 6).

Degradation involves either decomposing the coal, at the same time increasing the ratio by adding hydrogen (a process known as hydroliquefaction), or decomposing the coal to remove carbon (known as pyrolysis).

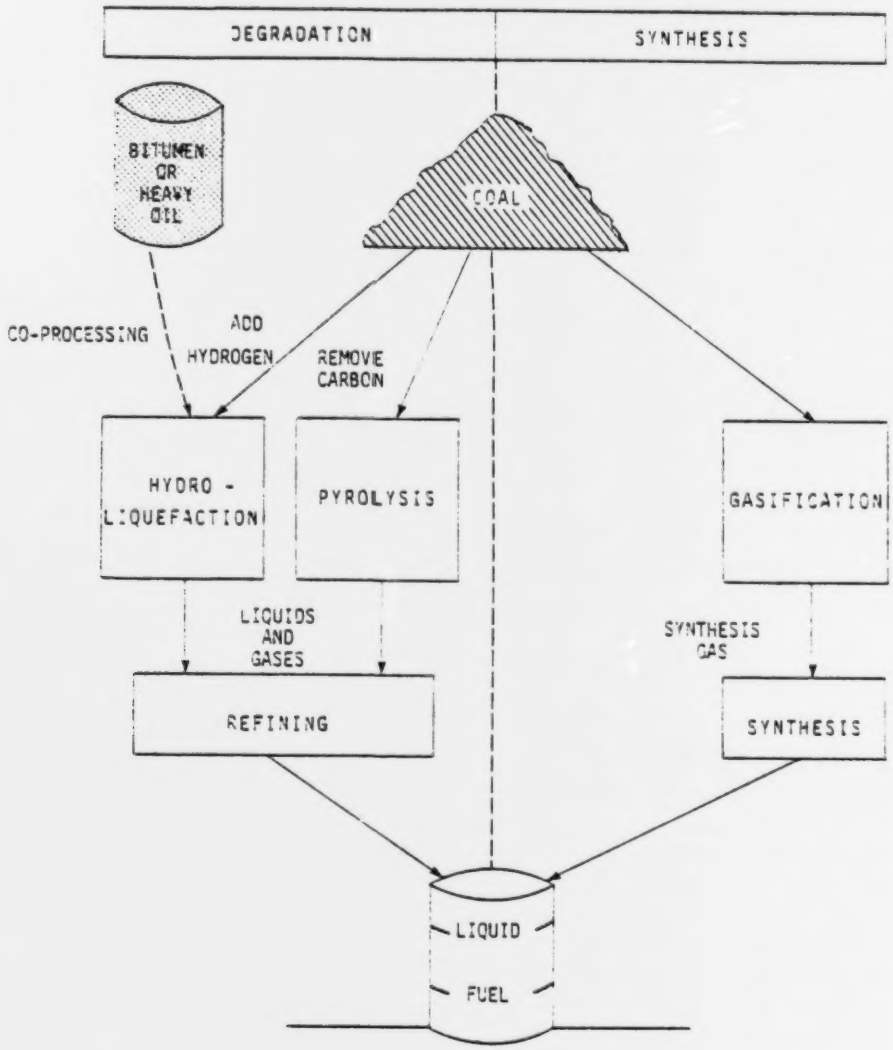

Figure 6 - Principal routes to liquid fuels from coal

In the synthesis route, gasification first converts the coal to simple gaseous components. The desired liquid products are then synthesized catalytically.

There are many possible variations, particularly in the degradation route. Each has advantages and disadvantages under given circumstances and each yields a particular product slate. (Product slate refers to the relative proportions of light, medium and heavy oils.) The fuels produced by synthesis can differ substantially from those produced by degradation.

The cost and type of product required governs the choice of conversion method. For example, for the boiler fuel markets, hydroliquefaction processes (Section 6.1.1), which produce heavy oil, are preferred. To produce a refinery quality feedstock suitable for transportation fuels, however, the heavy oil would have to be upgraded, through the addition of hydrogen. Upgrading could increase to the point where other liquefaction methods become more attractive.

Hydroliquefaction presently offers a better combination of liquid yield and thermal efficiency than pyrolysis or synthesis, as indicated by Figure 7. Thermal efficiency is defined as the percentage of the energy in the coal that is recovered in the products.

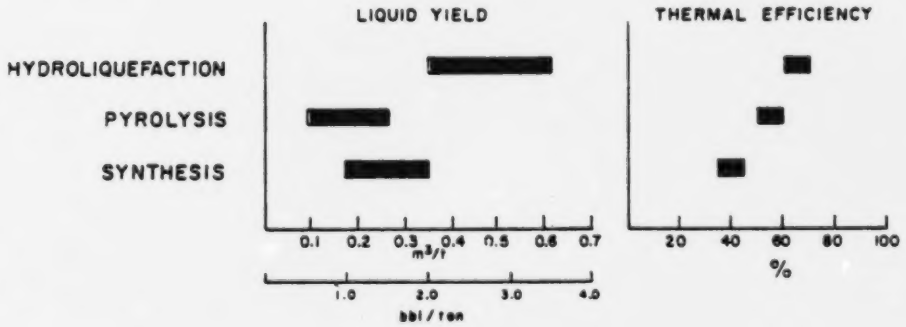

Figure 7 - Typical yields and thermal efficiencies in liquefaction routes

6.1 Degradation Processes

6.1.1 Hydroliquefaction

In hydroliquefaction (sometimes known as direct liquefaction), hydrogen can be either added as a gas or "donated" to the coal by a hydrogen-rich solvent to yield a liquid coal extract (Figure 8). The liquid extract can be distilled, hydrocracked and refined in an oil refinery.

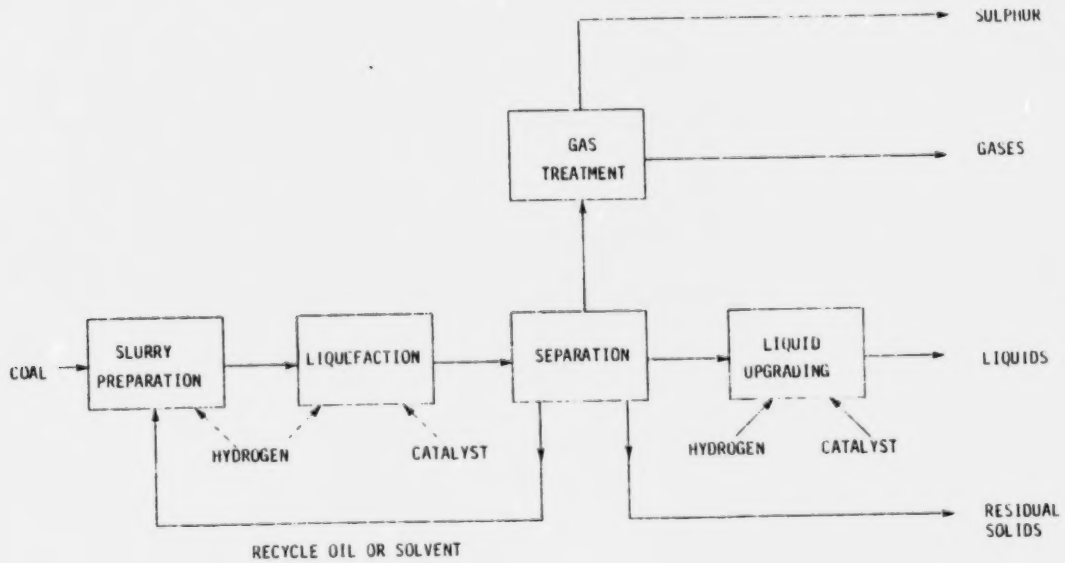

Figure 8 - Hydroliquefaction - generalized flow diagram

(The broken lines indicate that several options exist for the addition of hydrogen or catalyst in the primary stage.)

Some processes use a combination of the two approaches.

The coal liquefaction products are different from the fractions derived from petroleum. In general, the oils produced by coal liquefaction have a very limited hydrogen content and are highly aromatic. To be used as a petroleum substitute, these oils must be further processed, generally by hydrogenation, to yield marketable products.

Hydroliquefaction was the basis for the Bergius process which was used to produce much of Germany's liquid fuel supply during World War II. The coal-hydrogen reaction takes place in a slurry under high pressure and temperature in the presence of a catalyst. The liquid product is

distilled and the needed hydrogen can be produced from the solid residue by modern gasification technology.

The Bergius and its descendant processes rely on a catalyst for acceptable performance. The modern processes represent substantial improvements on the basic concept with respect to catalyst effectiveness; a better catalyst permits a lowering of temperature and pressure.

One of the most advanced catalytic processes is H-coal, (Appendix A.1.1), developed by Hydrocarbon Research, Inc. in the United States. It has high potential for early commercialization and is flexible with respect to feed characteristics and product slate.

Other hydroliquefaction processes using catalysts in the primary liquefaction stage include Synthoil, developed at the Pittsburgh Energy Technology Centre, C-E Lummus's Clean Fuels from Coal (CFFC) and Gulf's Catalytic Coal Liquefaction (CCL). The West Germans are also further developing the Bergius process, blending their previous experience with new concepts.

Catalysts have the drawback of being rendered ineffective due to contamination by coal impurities. Catalysts are expensive to replace and regeneration is difficult. Work is being carried out on catalyst development and also in processes that either use no catalyst, avoid direct contact between the coal and the catalyst, or are pseudo-catalytic (i.e. they take advantage of the inherent catalytic properties of coal mineral matter).

One approach is to eliminate the catalyst from the primary liquefaction step but still produce an extract that can be hydrogenated to a synthetic crude or low-sulphur fuel oil. This process is very flexible with respect to feed and products and uses a catalyst indirectly in that the recovered solvent is catalytically hydrogenated before it is recycled to the primary reactor. The principal developers are Exxon and Consolidation Coal Co. The Exxon process (Appendix 8.1.2) along with H-Coal and SRC-II (Appendix 8.1.3) has been identified as one of the most promising liquefaction technologies in the United States and is being scaled up to a large pilot plant (Appendix A.1.3).

A hydroliquefaction technique that may be particularly promising for Canada is the use of synthesis gas - hydrogen plus carbon monoxide - instead of pure hydrogen to hydrogenate coal. Known as COSTEAM, it improves liquid yields when used with low-rank coals and, like SRC-II,

takes advantage of the pseudocatalytic effect of the mineral matter. This type of process is being studied on a bench-scale with Canadian lignites in a CANMET[1]-funded project.

Researchers in the United Kingdom are studying a technology called supercritical gas extraction in which the solvent is present in a dense gaseous phase. It has several advantages over liquid phase operation. Solids separation, which is a problem area in most liquefaction schemes, can be achieved by simple temperature or pressure reduction to recover the solvent. Also, the liquid extract has a lower molecular weight and is therefore easier to refine than that obtained from liquid solvent extraction.

The supercritical gas process needs further development because even with optimum coals, extract yields tend to be low and large amounts of residual char are generated. The char might be suitable as a gasification feedstock or as a fuel for fluidized bed combustion.

Under optimum operating conditions, hydroliquefaction converts better than 95% of the organic coal substance to hydrocarbons and yields about 2.7 - 3.3 bbls of synthetic crude oil/ton.

The product slate can be varied by controlling the hydrogen transfer.

6.1.2 Pyrolysis

Pyrolysis, or carbonization, is simply the heating of coal to a temperature of 500 - 700°C in the absence of air. The decomposition that occurs results primarily in a carbon-rich coke or char, with hydrogen-rich tars, oils and gases as byproducts suitable for upgrading to liquid fuels (Figure 9). Hence from the point of view of liquid fuel production, pyrolysis is essentially a carbon removal operation.

Normally, no hydrogen is used in the basic pyrolysis process and liquid yields are low, making the process unsuitable as a primary liquefaction process. Liquid yields can be improved if temperatures are lowered, heating rates are faster or hydrogen is added. With the addition of hydrogen, a pyrolysis process is known as <u>hydropyrolysis</u> (or <u>hydrocarbonization</u>).

1 Canada Centre for Mineral and Energy Technology, Energy Mines and Resources, Canada.

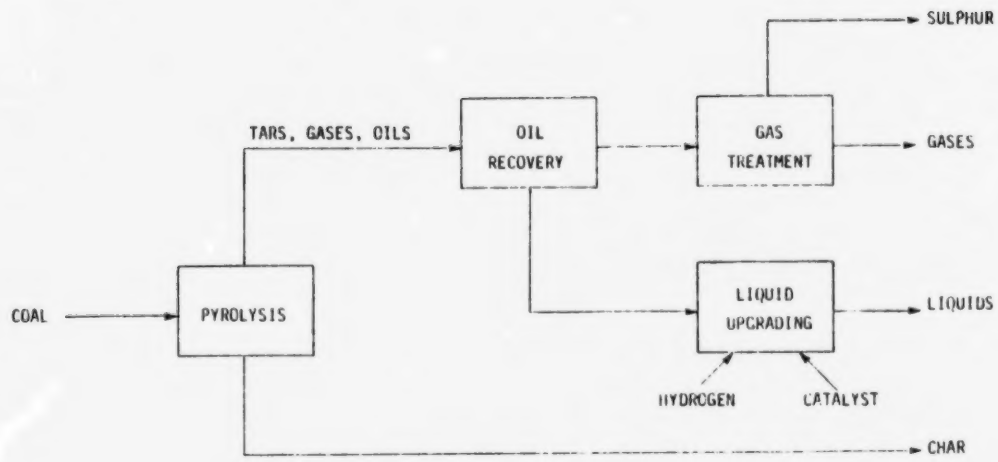

Figure 9 - Pyrolysis - generalized flow diagram

Pyrolysis is also common in the petroleum refining industry, where it is more commonly called coking. It is used to recover light liquid products from heavy residual oils and the process used to upgrade bitumen in the two commercial oil sands plants in Canada.

Coal pyrolysis schemes for liquid fuel production yield oils that can be hydrogenated to liquid fuels and byproduct gases. The principal problem appears to be marketing the large volumes of char produced, as it does not burn well. It may be possible either to gasify the char to useful fuel gases or to use residual char for thermal generation of electricity.

In Germany, the Lurgi-Ruhrgas pyrolysis process has reached the commercial scale on low-rank coals, but gives low liquid yields of about 20%. Several processes are under development in the United States by organizations including Cities Service, Occidental, Institute of Gas Technology, Oak Ridge National Laboratories and Rockwell International (Appendix 8.2). The highest reported liquid yield attained to date is about 35%.

Another pyrolysis technique is to heat the coal much more rapidly in the presence of hydrogen. This technique, known as flash hydropyrolysis, gives a char with improved burning properties, in addition to relatively high liquid

and gas yields. Because hydrogen is added, the process is a combination of hydroliquefaction and pyrolysis and could be used to produce both liquids and a solid boiler fuel (Reference 3).

6.2 Synthesis

Gasification, the reaction of coal with steam and oxygen at high temperature and pressure, yields a mixture of gases, principally carbon monoxide and hydrogen (referred to as syngas). If liquids are desired rather than gases, the mixture can be used to synthesize a variety of liquid hydrocarbons (Figure 10). The synthesis involves Fischer-Tropsch chemistry, another development pioneered in Germany before World War II.

Synthesis is inherently inefficient because the molecular bonds in the coal are first broken and then new ones created. It can, however, use a wide range of coals, including those high in ash and produces high-quality liquids. The synthesis step can be modified to vary the product slate within defined limits.

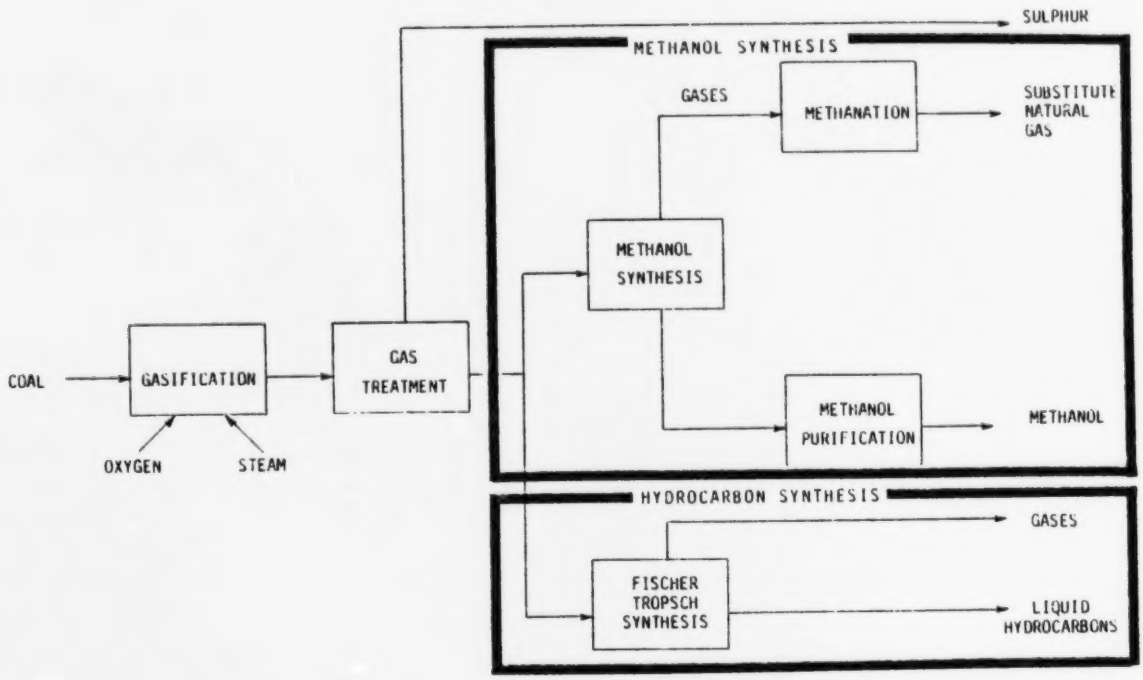

Figure 10 - Synthesis - generalized flow diagram

The problems in synthesis are similar to those of hydroliquefaction (Ref. Appendix 8.1.6), particularly relating to the gasifier.

6.2.1 Fischer-Tropsch Synthesis

In the Fischer-Tropsch synthesis, the syngas is passed over a catalyst and converted into a range of products from methane to waxes. That mixture is then run through a conventional refinery to yield liquid such as diesel fuel, jet fuel and gasoline.

The thermal efficiency of the Fischer-Tropsch synthesis is between 45 - 60%, depending on whether certain by-products are either used or sold. This efficiency range compares with 65 - 70% for direct liquefaction.

South Africa has become the most conspicious user of the German methods. The government-backed South African Coal, Oil and Gas Corporation (SASOL) uses Lurgi gasifiers to generate the syngas. The plant went on stream in 1955 and, following recent expansion, is expected to produce ultimately 50% of South Africa's oil consumption.

The SASOL complex produces methanol, gasoline, diesel fuel, fuel oil, ammonia, sulphur and a range of chemicals and coal-tar derivatives.

The current cost of SASOL oil is less than $20/bbl. Reasons for this low figure are:

(a) Cheap coal - about $10/ton (compared with more than $35/ton in B. C.).

(b) Low wage rates in South Africa.

(c) Capital costs amortized since 1955.

Capital costs for new plant for SASOL oil is high and the thermal efficiency is low (in the 45% range).

6.2.2 Methanol Synthesis

Syngas (CO plus H_2) can be converted to methanol, as described in Section 5.1. The methanol may then be converted to M-gasoline via the MTG processes (Ref. Section 5.2).

Mobil M-gasoline is reported to have a 35¢/gal advantage over Fischer-Tropsch gasoline at the plant gate.

6.3 Coal Selection

Selection of a processing route for coals depends on knowledge of the composition and properties of the available coal and how these properties bear on the technology being considered.

Knowledge of Canadian coal resources, other than deposits currently being mined, is still limited. More seriously lacking is a full assessment of the suitability of various coal deposits for particular uses.

Coal quality is not the most important factor in liquefaction economics. Coal cost is usually a much more significant determinant of viability. Thus, surface-mined low-rank coals, although they may not be the best coals for a particular technology, may be the most desirable because of their production cost.

The properties of coal which have the most significance on liquefaction include:

(a) Rank, which is measure of the geological maturity of coal. Figure 11 is the American Society for Testing and Materials method of classifying coals by rank.

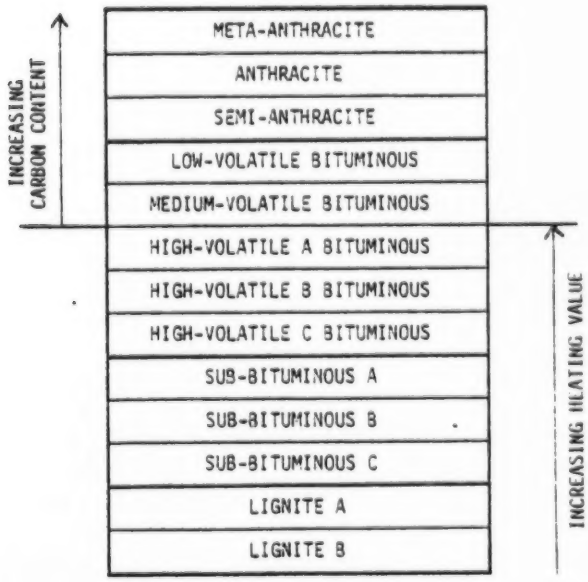

Figure 11 - Classification of coals by rank

The highest liquid yields are obtained with high volatile bituminous coals. Above or below that rank, yields decrease. Sub-bituminous coals and lignites liquefy most quickly and thus require less severe conditions of temperature-pressure. High rank coals tend to have lower hydrogen-to-carbon ratios (Figure 1). Because one objective of liquefaction is to increase this ratio, high rank coals should thus be more difficult to liquefy.

(b) Petrographic composition. Petrography is the science of classifying coal as a rock (i.e. by its organic and mineral constituents, known as macerals).

Briefly, maceral composition influences chemical reactivity during processing. In hydroliquefaction, dissolution of reactive macerals can help bring about effective hydrogen transfer.

(c) Reactivity. A more reactive coal liquefies faster and to a greater extent.

(d) Mineral Matter. Although undesirable because it does not convert to liquids and creates a residue, mineral matter appears to exhibit a catalytic effect during liquefaction.

(e) Sulphur in coal is undesirable from the environmental aspect, although it can act as a catalyst and a certain amount may be desirable. Sulphur removal can be costly.

6.4 Coal Requirements for a Liquefaction Plant

Before a commercial liquefaction plant can be established, sufficient coal to feed the plant over its expected life must be assured.

The optimum capacity to make a coal liquefaction plant economic is usually considered to be 100,000 bbl/day of liquid product, four-fifths the size of the Syncrude oil sands refinery. Assuming an optimistic liquid yield of 3 bbl/ton of coal, such a plant would use about 30,000 tons/day. This would amount to 11×10^6 tons/annum, about 35% of the total. If the product were a synthetic crude, it would supply less than 5% of today's national needs.

If the recovery factor in surface mining and preparation were assumed to be 60%, the total required coal in place over the minimum 20 year life of the plant would be about 360×10^6 tons. There are between six and ten sites that could support such a facility, all in Western Canada. This assumes a mine-mouth plant to reduce costly haulage requirements.

Coals suitable for liquid fuel production lie in Nova Scotia, New Brunswick, Ontario, Saskatchewan, Alberta and British Columbia. The deposits in Alberta and Saskatchewan are particularly large.

In British Columbia substantial deposits of bituminous coals occur in the southeastern and northeastern parts of the province. These coals are of excellent coking quality and their use for coking is preferable to liquefaction.

Several other deposits of lower-grade coals occur in the south-central parts of B. C., but most are too small or difficult to mine to be considered for liquid fuel production.

The Hat Creek is a very thick, near surface lignitic to sub-bituminous bed. High ash, moisture and oxygen contents and low liquid yields make hydroliquefaction or pyrolysis of the Hat Creek coals technically impractical. A synthesis route to make liquid fuels or petrochemicals may be more feasible.

Liquefaction experience with Canadian coals has been very limited, and current assessments of their potential are generalizations based largely on theoretical considerations and on experience with similar coals elsewhere. Actual experimental trials will be necessary to properly evaluate their behaviour in liquefaction processes.

6.5 Problem Areas

Current developments are concerned with reducing reaction temperatures and pressures.

In most experimental plants, there have been several recurring problems common to most processes. As the processes approach commercialization, these problems begin to be measured in dollars, particularly as scale-up can aggravate them.

Examples of the most significant problems are given in Sections 6.5.1 - 6.5.4.

6.5.1 Process Problems

Process problems generic to coal liquefaction include:

(a) Measurement and control of process control streams.

(b) Measurement and correlation of stream properties.

(c) Materials and components which have to withstand the severe operating conditions.

(d) Gasification, cleanup and recycle.

(e) Heat recovery from dirty process streams. Heat recovery is essential to efficient operation.

6.5.2 Hydrogen Supply

Hydrogeneration requires large quantities of hydrogen. Costs and methods of hydrogen production are receiving serious attention.

Currently, almost all the hydrogen used in Canada is made by steam reforming of natural gas - the cheapest method in most cases. Other methods include steam reforming of naptha and refinery off-gases, gasification of coal or liquefaction residues and nuclear-assisted electrolyses.

Further analysis may reveal that use of liquefaction residues would substantially improve plant economics, particularly as it would also reduce waste disposal requirements.

6.5.3 Coal Science

A better fundamental knowledge of the effects of feedstock characteristics on product quality and process operability might improve yields and thermal efficiencies, reduce capital costs, and help avoid costly shut-downs. Such knowledge is necessary for a full evaluation of the suitability of Canadian coals for liquefaction. Of particular interest are the petrographic and chemical characteristics of the coals, of which knowledge is superficial.

6.5.4 Environmental Impact

The principal emissions of concern are large quantities of gaseous, liquid and solid effluents, as well as waste heat, although undesirable noise and odours are also produced. Gaseous and liquid emissions could probably be dealt with by conventional means employed in petroleum refineries.

Solids disposal and waste treatment could be a problem. A 100,000 bbl/day facility could use about 30,000 tons coal/day. With a feed each of, say, 15% mineral matter, 4,500 tons of waste mineral matter would be rejected daily.

Liquid and plant effluents are carcinogous and thus present a health hazard. Additionally there is a concern over the radioactivity of coal ash.

Water supply could also be a problem, depending on plant location, output and process selected. Water is required for cooling and hydrogen production.

6.6 Costs

Most economic studies have shown that liquid fuels from coal are currently not economically competitive with those derived from conventional crude oil or oil sands. The estimated selling price for synthetic crude is between $18 and $35/bbl.

Economic analysis for coal liquefaction schemes vary widely and the bases for such analyses must be clearly established before cost estimates can be acceptable.

A realistic economic analysis should be based on the value of the refined products (i.e. of liquid fuels), or must take into account the extra processing needed to bring coal syncrude up to refinery specifications. It must also take into account coal quality, plant location, necessary infrastructure and a variety of other economic factors.

Table I summarizes a design and economic study of the EDS process by Exxon. This study showed a price of $29/bbl (1978 - US $) for the liquid products.

Table I Exxon Donor Solvent Commercial Plant Study Design

(1978 - US $)

Coal Type	Illinois No. 6
Coal feed rate, tons/day	24,000
Yields, bbl/day	
C_3 - C_4 LPG	8,000
C_3 - 400°F Naptha	22,000
Fuel Oil (0.5 wt % S)	29,800
Total Liquids	59,800
Capital Investment, $ Billion (1978)	1.6
Initial Selling Price, $/bbl (1978)[b]	29
Overall thermal efficiency	63%

[a] Source: Refs. 6, 7

[b] Basis: 100% equity at 15% DCF return, 5% cost inflation, 6% product price inflation.

Exxon has compared the cost of liquids from SRC-II, H-Coal and the EDS processes and concluded that the costs of all three appear to be within ± 10% of each other (Reference 4).

A study by Mobil Oil indicates that the Mobil-M process is superior to Fischer-Tropsch from the standpoint of thermal efficiency and product cost. The results are summarized in Table II.

Table II

Economic Comparison of Mobil-M and Fischer-Tropsch Based on Wyoming Subbituminous Coal and Lurgi Gasifiers[8] (1977 - US $)

	Mobil-M (Fluid Bed)	Fischer-Tropsch
Coal Feed Rate, TPD	27,300	27,800
Products, bbl/day		
Gasoline	23,065	13,580
SNG	152	173
C_3LPG	1,790	1,107
C_4		146
Diesel Fuel		2,307
Fuel Oil		622
Alcohol		510
Total Fuel Oil Equivalent, bbl/day	45,560	44,950
Overall Efficiency, %	63	58
Capital Investment, $ Billion (1977 - US)	1.68	1.89
Product Cost, $/million btu[b]	6.80	7.78
Gasoline Cost, $/gal[c]	0.83	0.93

[a] Source:
M. Schreiner, "Research Guidance Studies to Assess Gasoline from Coal by Methanol-to-Gasoline and Sasol-type Fischer-Tropsch Technologies, Final Report," FE-2447-13, August 1978.

[b] All products valued equivalently on btu basis.

[c] 100% equity financing, 12% return on investment, all costs in 1977 dollars.

Generalized cost breakdowns are given for the hydroliquefaction case in Tables III and IV to indicate the economic features of a typical liquefaction facility.

Table III

Average capital cost breakdown for a 50,000 bbl/day hydroliquefaction facility

Total capital cost \$850-950 X 10^6 (1978)	% of Total
*Coal storage and preparation	10
Primary hydrogenation step	30
Hydrogen production	25
Utilities and facilities	25
Product and byproduct handling and treatment	10

*Does not include mine

Table IV

Annual operating cost breakdown for a 50,000 bbl/day hydroliquefaction facility - Range of estimates

Item	%
Coal	30 - 60
Catalysts and chemicals	2 - 15
Labour	2 - 10
Utilities	3 - 6
Fixed costs (overhead, taxes, etc.)	4 - 12
Capital charges	30 - 45
Other	5 - 10

6.7 State of the Art

Coal liquefaction research and development is underway in several countries, with the United States, West Germany and the United Kingdom leading the way in the non-Communist world. The only commercial facility is in South Africa.

In Canada, the effort in research and development of coal liquefaction processes has been small compared to the above countries. Much work is required particularly in the assessment of the suitability of Canadian coals for liquefaction.

The federal Energy, Mines and Resources department, the Sandwell-Beak Research Group in Toronto and the Nova Scotia Research Foundation are each to have a continuous bench scale coal liquefaction unit under construction (Reference 5).

Algas-EMR and the Alberta Government are involved together in a project to identify the economic feasibility of a coal liquefaction plant in western Canada.

It will probably take at least 15 years before a synthetic fuels industry can be developed sufficiently to make a significant contribution to the supply of liquid fuels. It is not at all clear that natural market place forces will be able to build the industry rapidly enough to meet the demands expected in the next 20 to 30 years.

Table V gives some long range forecasts for a variety of energy sources in the US.

Table V

Estimates of Market Penetration of Energy Technologies

	1985	1990	2000
Energy source, quads[1]			
Enhanced oil recovery	2.1-2.7	3.6-5.9	10.7-17.2
Enhanced gas recovery	1.4-2.6	2.7-7.6	2.7-7.8
Oil shale	0.4-0.8	1.0-2.0	4.0-8.0
Gas, high btu	0.16-0.24	0.4-0.9	2.0-2.5
Gas, medium btu	0.04	1.0	2.0
Gas, low btu	0.02	0.2	0.4
Utility atmospheric fluidized bed	0	3.0	3.0
Industrial atmospheric fluidized bed	0.3	1.0	1.6-3.0
Low-head hydroelectric	0.02-0.07	0.1-0.4	0.3-1.0
Hydrothermal and geothermal	0.03	1.6	1.6-2.1
Coal liquids	0.013	0.7	2.8
Large wind	0.04	0.2	2.1
Total	4.75-7.20	12.4-21.4	31.1-49.8

1. One quad equals 10^{15} btu (~ 10^{18} J).

(1) Source: Engineering Societies Commission on Energy Inc., Washington, D. C.

7. CONCLUSIONS

7.1 Liquid fuel from coal will probably gain in importance because it can be used interchangeably with oil. It is not expected to be available for wide distribution much before the 1990's, however.

7.2 Oil produced by coal liquefaction in areas of relatively cheap coal, e.g. mid-Western US and Western Canada could be competitive with imported oil now. The only proven technologies (methanol, Lurgi-plus-methanation and Fischer-Tropsch) are relatively inefficient, however.

7.3 Each liquefaction technology has its own merits in particular circumstances. The choice of technology will ultimately be based on desired products, coal characteristics and cost.

7.4 Extensive work is being carried out to improve efficiency. The most efficient technology in coal liquefaction is currently only at the pilot plant stage.

7.5 Scaling up from pilot plant to commercial size can be difficult. Pilot plants are designed to yield information, not make money. Relatively minor problems (such as frequency of valve repairs) on a pilot plant could become major maintenance requirements on a large plant.

7.6 From the environmental aspect, there are many problems to be resolved before liquefaction on a commercial scale becomes generally acceptable.

7.7 In view of the ever rising price of imported oil and the lead-time for technological development and plant construction, the main problem is to decide whether it is better to proceed with coal liquefaction now using relatively inefficient, but proven, technology, or to wait until efficient processing has been developed.

Canada may not be able to obtain oil self-sufficiency within a practical time frame unless a significant part of future liquid fuel supplies are derived from coal. Decisions on coal liquefaction programs, then, are based essentially on how much is prepared to be expended to ensure that future demands for liquid fuels can be met.

8. APPENDIX - DEGRADATION PROCESS OUTLINES

8.1 Hydroliquefaction

The three American single-stage liquefaction techniques which have the best prospects for commercialization are discussed in Section A.1.2 - A.1.3. These processes are all similar in that a slurry of coal in process derived oil is subjected to fairly severe liquefaction conditions in the presence of hydrogen.

An example of two-stage liquefaction is discussed in Section A.1.6.

None of these processes have yet operated in an integrated fashion and, therefore, variation in practice may be made for technical or economic reasons.

8.1.1 H-Coal Process

The H-Coal process was developed by Hydrocarbon Research Inc. and Ashland Oil and is shown in the flow diagram (Figure 8.1).

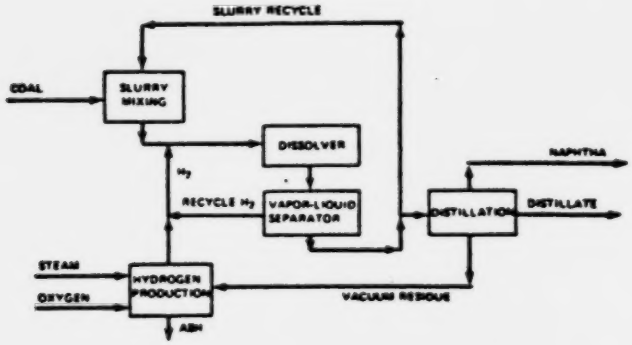

Figure 8.1 - Flow diagram of H-COAL Process

The H-Coal Process is a direct hydrogenation process employing catalytic materials in direct contact with both coal and the solvent to promote liquefaction. The process converts high sulphur coal to a boiler fuel or synthetic crude oil which may be further refined to transport fuels.

Coal is slurried with a process-derived oil, pumped to a reactor vessel, mixed with recycle and make-up hydrogen and fed through a preheater to a catalytic reactor which

is fluidized. Typical operating conditions are 2,500 - 3,000 psi and 450°C. The reactor products are then separated in a vapour liquid separator for subsequent processing.

A portion of the reactor feed is hydrocloned to reduce its solids content and prepare a low-solids liquids stream for recycle to the feed slurry preparation tank. The remainder of the liquid product is vacuum distilled to produce naptha and distillate fuel oil plus a bottoms stream which goes to a gasifier for hydrogen production.

A 600 ton/day pilot plant operated by Ashland Oil and its partners is currently under construction at Catlettsburg, Ky and is designed to produce 2,000 bbls/day of low sulphur boiler fuel. Additionally, the plant can be run to produce a lighter range of liquids. A commercial plant is under consideration to produce 50,000 bbls/day.

Estimated product costs vary with the assumed coal price and discounted cash flow rate of return. Based on a $30/ton coal price and 12% rate of return, the product price is estimated at about $20/bbl.

8.1.2 Exxon Donor Solvent (EDS) Process

This is an indirect catalytic process which employs a hydrogen donor solvent obtained from distillate coal products. High yields of low sulphur liquids can be produced from bituminous and subbituminous coals or lignites.

In this process (Figure A.2) the coal is slurried with a recycle donor solvent which has been catalytically hydrogenated to improve its hydrogen donor properties. The slurry is preheated and goes to the reactor along with recycle and make-up hydrogen. The reactor operates at about 2,000 psi and 425 - 475°C. There is no added catalyst. The reactor effluent is distilled to obtain the recycle solvent which is then rehydrogenated in a fixed bed catalytic reactor.

The liquid products are distillates. Unreacted coal and ash are removed from a vacuum distillation column and go to a gasifier unit for recovery of additional liquids and production of fuel gas. Make-up hydrogen is produced by reforming the light hydrocarbon gases produced during liquefaction.

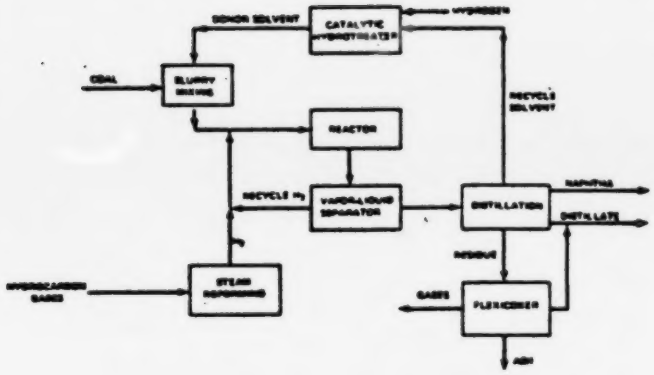

Figure 8.2 - Flow diagram of EDS Program

Exxon have almost completed the construction of a 250 ton/ day pilot plant for an estimated cost of $280 million (US) (Reference 6).

8.1.3 Solvent Refined Coal - SRC-II

The non-catalytic SRC-II process (a modification of the SRC-I process which produced a solid fuel in addition to a liquid fuel) is based on the fact that the greater the hydrogen content of a liquid fuel, the lighter the fuel. The SCR-II process thus yields mostly fuel oil, along with lighter fractions, such as naptha (Reference Figure 8.3).

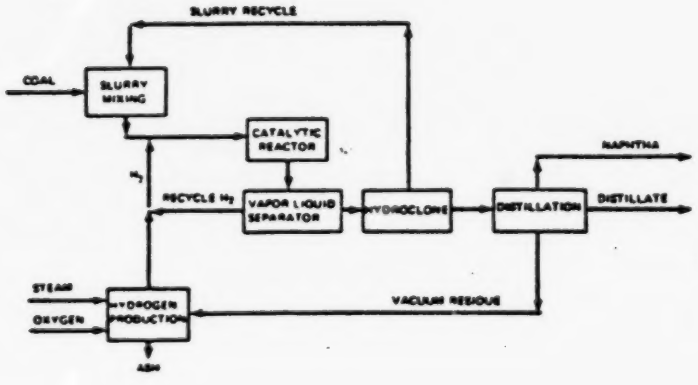

Figure 8.3 - Flow diagram of SRC-II Process

The SRC-II process involves recycle of a portion of the product slurry as a "solvent". Recycle of the slurry makes it possible to hydrocrack much of the dissolved coal to a distillate liquid product. Since the quantity of dissolved coal remaining is then relatively low, it becomes practical to feed this material to a gasifier, together with the undissolved mineral residue. This means that the primary product from the process is a distillate fuel oil.

The major problems encountered with SRC-II fuel oil combustion are the high NO_x emissions when controls are not employed. The NO_x emission aspect is a subject for further work.

From the fuel user's perspective, SRC fuel oil represents a high-heating value, environmentally clean, storable distillate fuel with practically all of the ash removed through vacuum distillation. More than 90% of the sulphur and more than 50% of the nitrogen have been removed (on a btu basis). It appears that most all of the trace metals are removed as well. This is of particular interest for the potential use of SRC fuel oil as a turbine fuel as well as a boiler fuel.

The commercial prospects for SRC fuel are directed toward the large utility and large industrial oil and gas users of the 1990's. An SRC refinery will produce principally fuel oil plus substantial quantities of synthetic pipeline gas, LPG, and an aromatic naptha (see Table A.1).

Table A.1 - Solvent Refined Coal Products

For demonstration module with 6,000 t/day coal feed and commercial (five module) with 30,000 t/day high-sulphur coal feed

Product	Quantity		Application
	Demo Module	Commercial	
Ammonia, Anhydrous	24 t/day	120 t/day	fertilizers
Sulphur	170 t/day	850 t/day	sulphuric acid manufacture
Pipeline gas	15 mmscf/day*	36 mmcf/day	residential heating
LPG	990 bbl/day	7,700 bbl/day	residential and commercial heating and industrial fuels
Naptha	3,400 bbl/day	15,000 bbl/day	low sulphur, ashless utility and industrial fuel
Phenols	--	20 bbl/day	chemical feedstock

*If naptha is utilized as plant fuel in demo module, pipeline gas is increased to 34 mmcf/day.

The US Department of Energy has contracts for the design of the first modules of commercial plants based on the SRC-I and SCR-II processes. Each module should produce 20,000 bbls/day of the low S fuel. Coal input will be 6,000 tons/day.

The anticipated investment required to build a 50,000 bbl/day liquefaction plant is about $1 billion (US).

A multiple-train full size SRC refinery feeding 30,000 tons of high-sulphur bituminous coal per calendar day would produce fuels having the equivalent btu output of a 100,000 barrel per day petroleum refinery.

Cost of oil from the SRC-II process has been estimated at $30 - 40/bbl (US $).

8.1.4 Pilot Plant Schedule

Figure 8.4 summarizes the schedules for the large pilot plants and demonstration plants for the single-stage liquefaction processes.

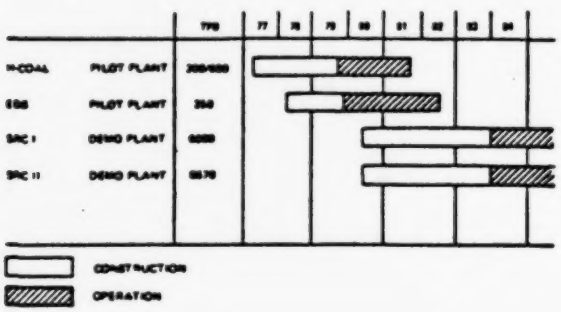

Figure 8.4 - Direct Liquefaction Pilot Plant - Demo Plant Schedule

8.1.5 Two-Stage Liquefaction

In two-stage liquefaction, there is an initial dissolution step followed, after removal of most of the solids, by a severe hydrogenation. A simplified flow diagram is shown in Figure 8.5.

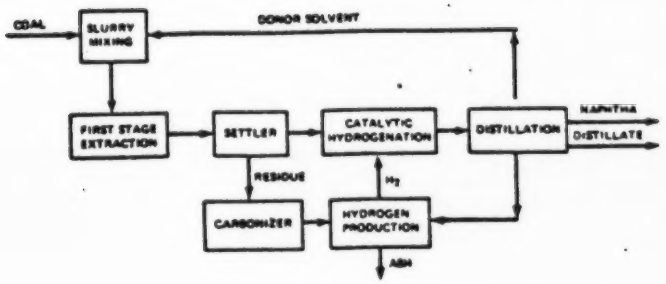

Figure 8.5 - Flow diagram of two-stage liquefaction (CSF)

Integrated operation for two-stage liquefaction has not yet been demonstrated. The Conoco Coal Development Company's CSF Process is at the pilot-plant stage of development (Reference 7).

The main advantage claimed for the CSF process is that the settling out of most of the mineral matter and unreacted coal has the effect of reducing expensive cobalt-molybdenum catalyst consumption.

8.1.6 Problems in Hydroliquefaction

Major problems in hydroliquefaction include the following:

(a) Valves in slurry service have shown rapid wear and a short life due to the erosive actions of the slurry at high velocities. In a commercial plant, replacing these valves during operation could present design and operational complexities.

(b) Design of a fired heater to preheat the slurry is difficult because of coal behaviour and lack of heat transfer data.

(c) In catalytic processes, catalyst activity and life are major concerns.

(d) Solid/liquid separation is particularly troublesome and much work is being done in this area.

(e) Most of the liquefaction processes require a gasifier for the production of hydrogen or fuel gas from the unconverted coal residue. Development of a high pressure gasifier for this application carries with it its own set of concerns, such as the pressurized feed system and ash or slag removal.

(f) Heat recovery from reactor effluent is difficult due to fouling and coking. If heat recovery is not practised, however, there is a thermal efficiency penalty.

8.2 Pyrolysis

Figure 8.6 is a conceptual flow diagram for hydropyrolysis. The Rocketdyne Division of Rockwell International has demonstrated (in a one ton/h reactor) a process based on the concept that high liquid yields are favoured when coal is allowed to react with hydrogen at high temperature for a short period of time followed by rapid quenching. Reaction temperatures of about 750 - 1,000°C are achieved by mixing the coal preheated with hydrogen preheated to about 1,000°C. Rockwell claim to have achieved carbon conversion to liquid products of about 20 - 30%. In a commercial plant design, it is expected that the unreacted char would be fed to a gasifier to produce hydrogen for fuel gas as required by the facility (Reference 2).

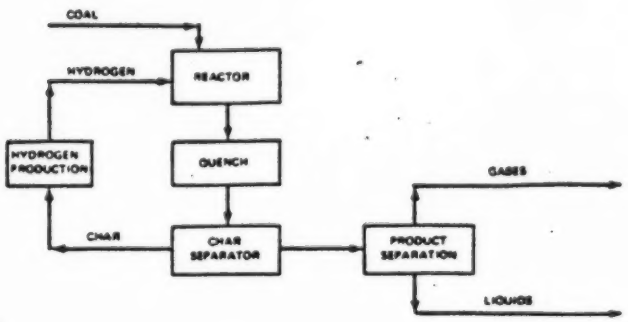

Figure 8.6 - Flow diagram of rapid-hydropyrolysis

The COGAS process (Reference 8) in which char is gasified, is one of two processes under consideration for a large (2,200 ton/day) demonstration plant to produce pipeline quality gas from coal. The COGAS plant, if built, will produce nearly half of the heating value of its products as liquid fuel. The other contender is the Conoco Coal Development Company's proposal using the British Gas Corporation - Lurgi slagging gasifier.

Among problems specific to pyrolysis processes are the handling of dry solids at elevated temperatures and pressures.

Rockwell, Westinghouse and Union Carbide appear to have developed methods for handling coking coals in pyrolysis reactors. Large scale demonstrations have not been attempted to any of these approaches, however.

Providing process heat to pyrolysis reactors affects the process thermal efficiency and an entirely satisfactory method of doing this has yet to be found. The use of char to provide process heat is an objective currently requiring study.

Other areas in pyrolysis processes requiring research are:

(a) heat recovery from reactor effluents
(b) gas/solid separation techniques
(c) a full understanding of the process chemistry and kinetics to control the process better
(d) toxological and environmental problems in the use of pyrolysis liquids.

To be commercially viable, any pyrolysis scheme must be coupled with a way to use the char. There are a number of other critical technical problems and more information is required on the gas/solids separation associated with the liquid products.

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